Composite Dirac neutrinos with QCD axion

Tae Hyun Jung
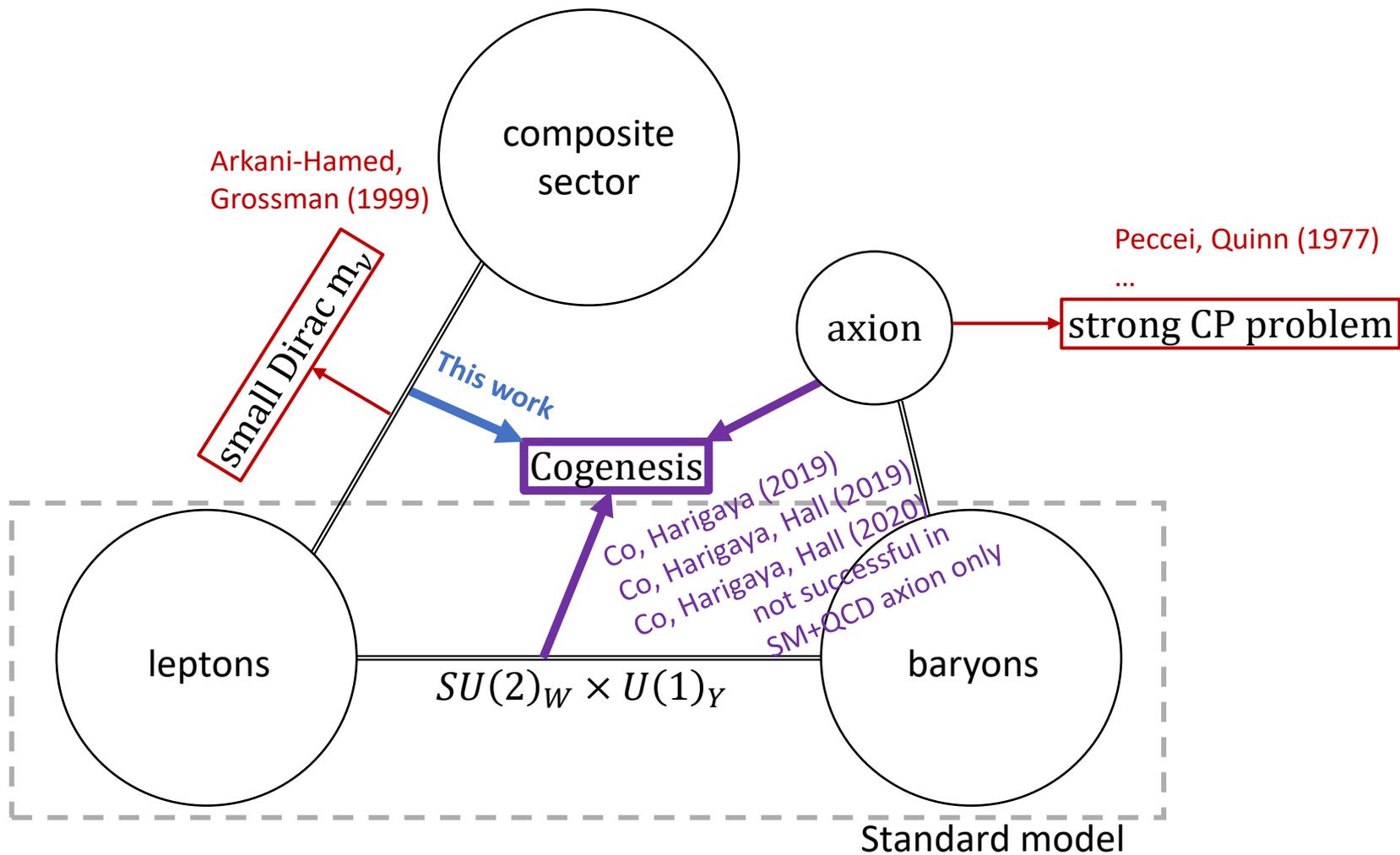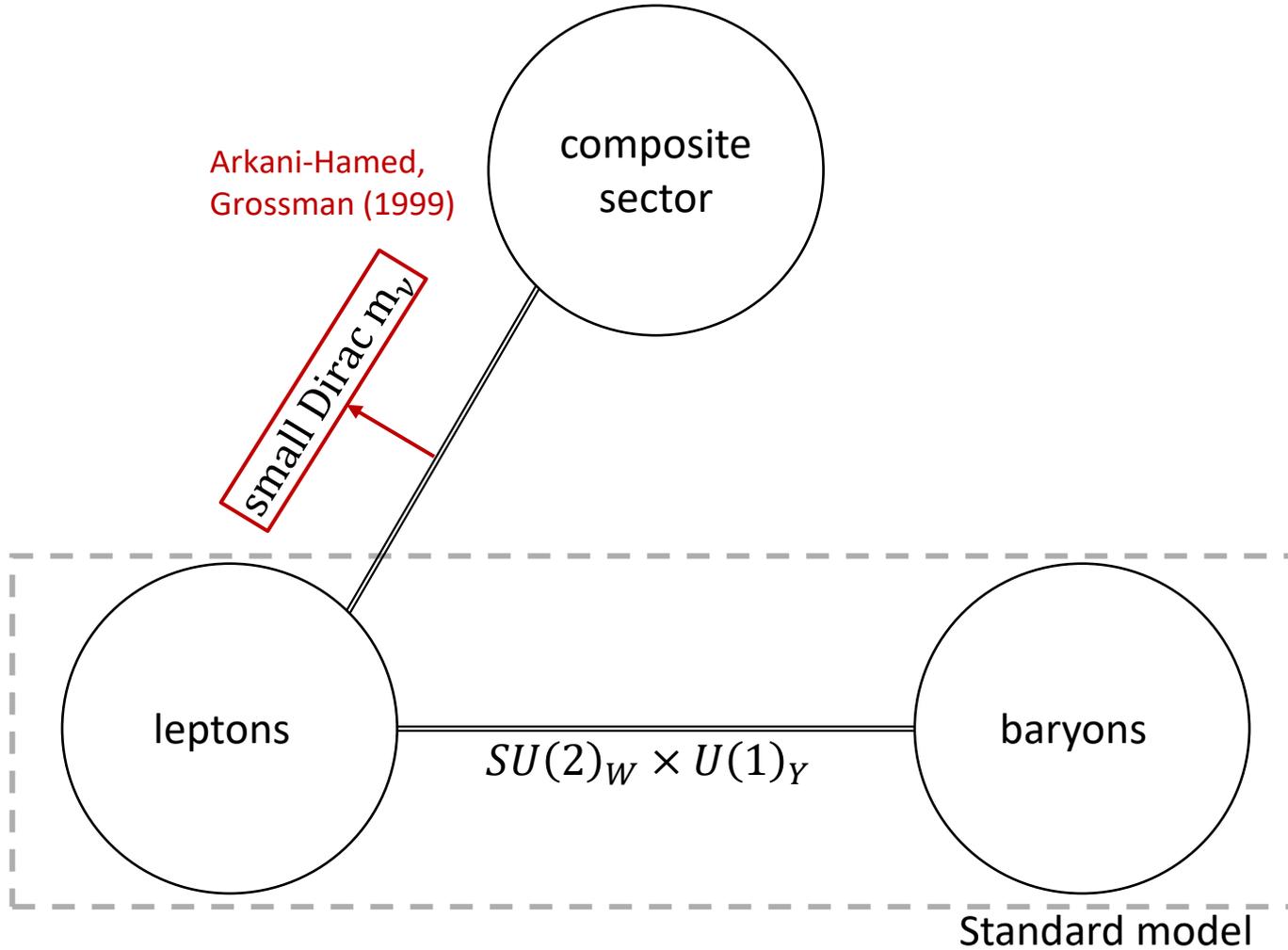
KIAS
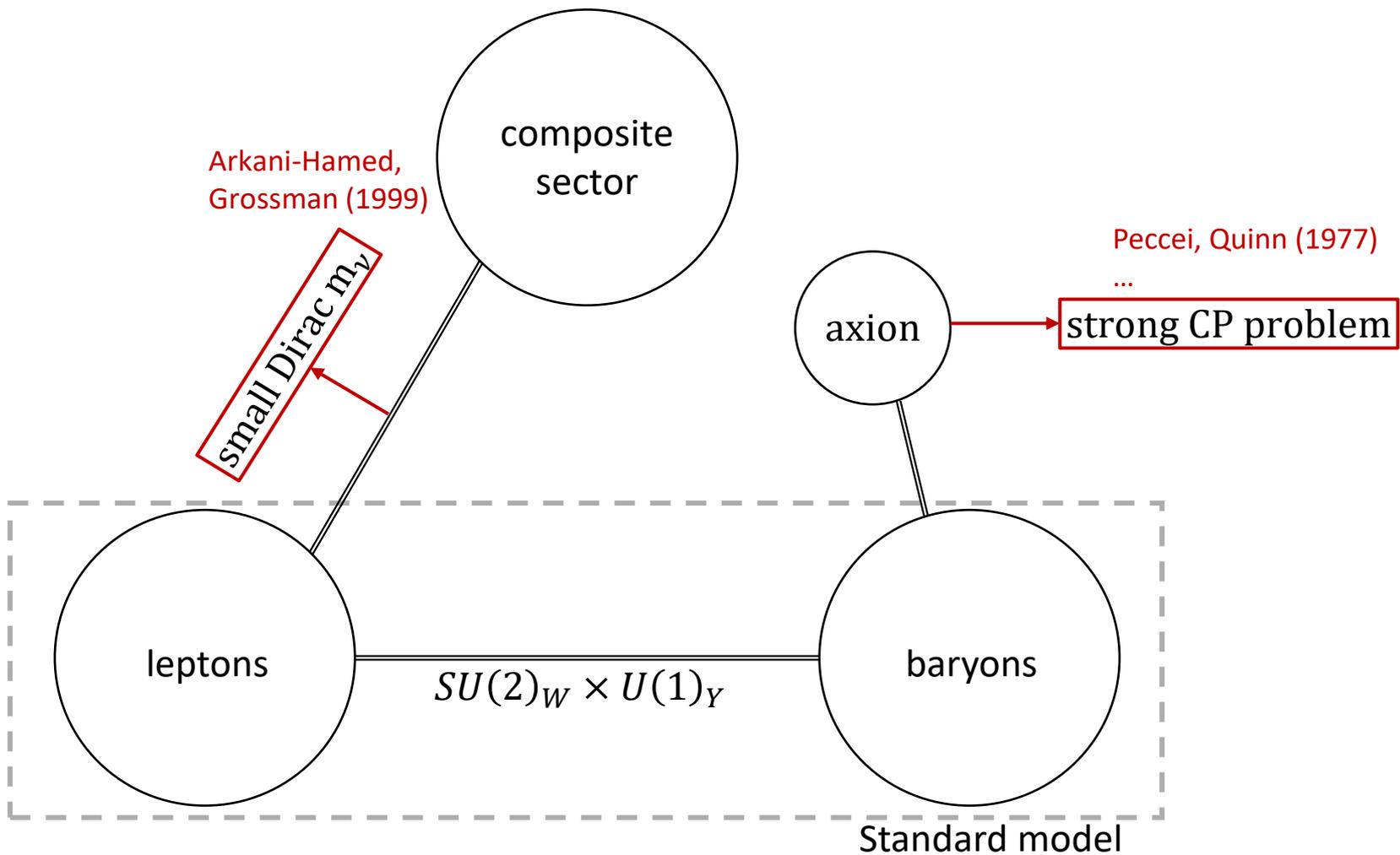
Outline

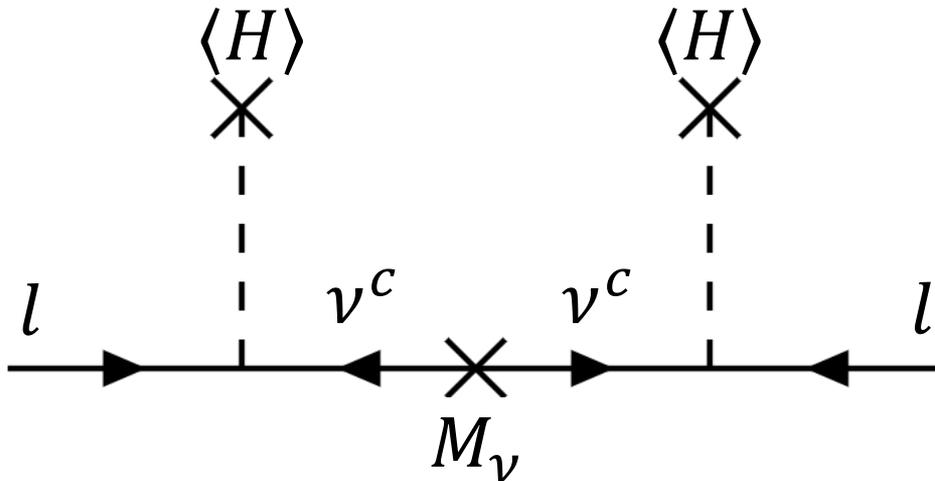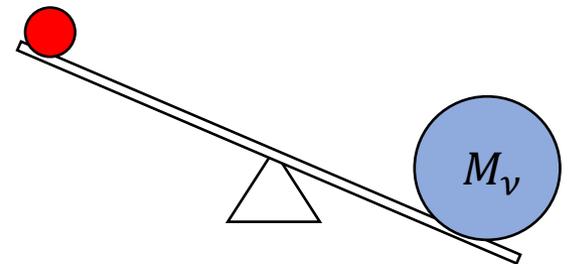# Outline

Composite Dirac neutrinos

Why are neutrinos so light?

$$y_\nu \, H \, l \, \nu^c + \text{h. c.} + M_\nu \nu^c \nu^c$$

1. See-saw mechanism (Majorana neutrinos): $M_\nu \gg y_\nu v_h$

$$\Rightarrow m_\nu \sim y_\nu v_h \left(\frac{y_\nu v_h}{M_\nu} \right)$$

2. $0 \neq y_\nu < 10^{-13}$ without $\underline{M_\nu}$

N. Arkani-Hamed, Y. Grossman (1999)

Composite ν^c

Composite Dirac neutrinos

$$\nu^c \propto \psi\psi\chi$$

ψ, χ: fundamental Weyl

ν^c: composite Weyl (like proton/neutron in QCD: $p \propto uud$, $n \propto udd$)

Effective description
after confinement

Fundamental description
before confinement

$$H\, l\, \nu^c \quad \leftrightarrow \quad \frac{1}{M^3} H\, l\, (\psi\psi\chi) \longrightarrow \underline{\text{Dim: 7}}$$

$$(\psi\psi\chi) \sim \Lambda_c^3\, \nu^c$$
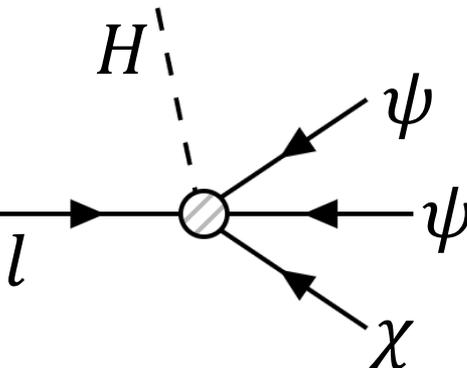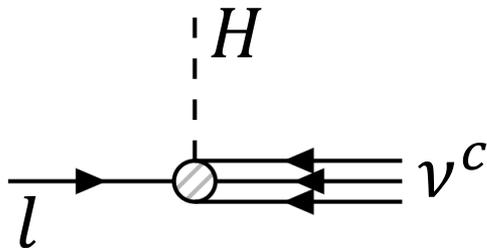
$$\boxed{y_\nu \sim \left(\frac{\Lambda_c}{M}\right)^3}$$

$$\frac{\Lambda_c}{M} \sim 10^{-4} \Rightarrow m_\nu \sim 0.1 \text{ eV}$$

∗ Majorana operator $(\psi\psi\chi)^2$: dim 9

Q: How can those composite <u>fermions</u> remain massless?
cf) baryons in QCD

→ **A special setup required**

Composite Dirac neutrinos

Arkani-Hamed, Grossman (1999)

	Gauge
	$SU(6)$
ψ	$\overline{\mathbf{6}}$ $\times 2$ (Two generation)
χ	$\mathbf{15}$
$\nu^c \propto \psi\psi\chi$	$\mathbf{1}$ $\times 3$ (Three generation)

Composite Dirac neutrinos

Arkani-Hamed, Grossman (1999)

	Gauge	Global	
	$SU(6)$	$U(1)_X$	
ψ	$\overline{\mathbf{6}}$	$-2/3$	$\times$ 2 (Two generation)
χ	$\mathbf{15}$	$1/3$	
$\nu^c \propto \psi\psi\chi$	$\mathbf{1}$	-1	$\times$ 3 (Three generation)

$$A(U(1)_X SU(6)^2) = 0$$

Composite Dirac neutrinos

Arkani-Hamed, Grossman (1999)

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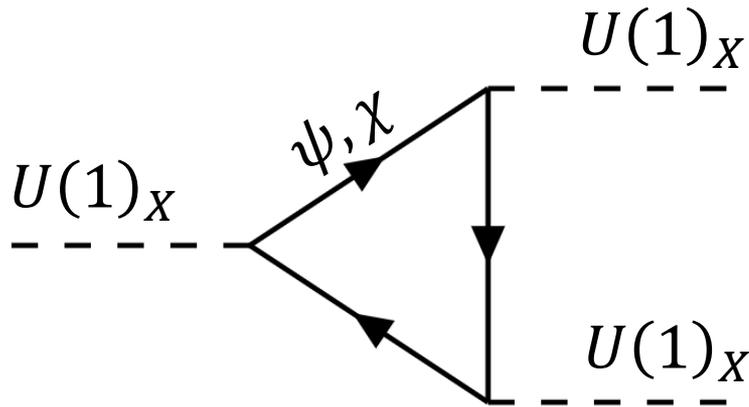
UV $= -3$ **IR**

’t Hooft anomaly matching conditions

S. Dimopoulos, S. Raby, L Susskind (1980)

Composite Dirac neutrinos

Arkani-Hamed, Grossman (1999)

	Gauge	Global	
	$SU(6)$	$U(1)_L$	
ψ	$\overline{\mathbf{6}}$	$-2/3$	× 2 (Two generation)
χ	$\mathbf{15}$	$1/3$	
$\nu^c \propto \psi\psi\chi$	$\mathbf{1}$	-1	× 3 (Three generation)
l	$\mathbf{1}$	$+1$	× 3 (Three generation)

Interaction with SM: $\dfrac{\Lambda_c^3}{M^3} H l \, \nu_c \sim \dfrac{1}{M^3} H l \, (\psi\psi\chi)$

$B - L$: good

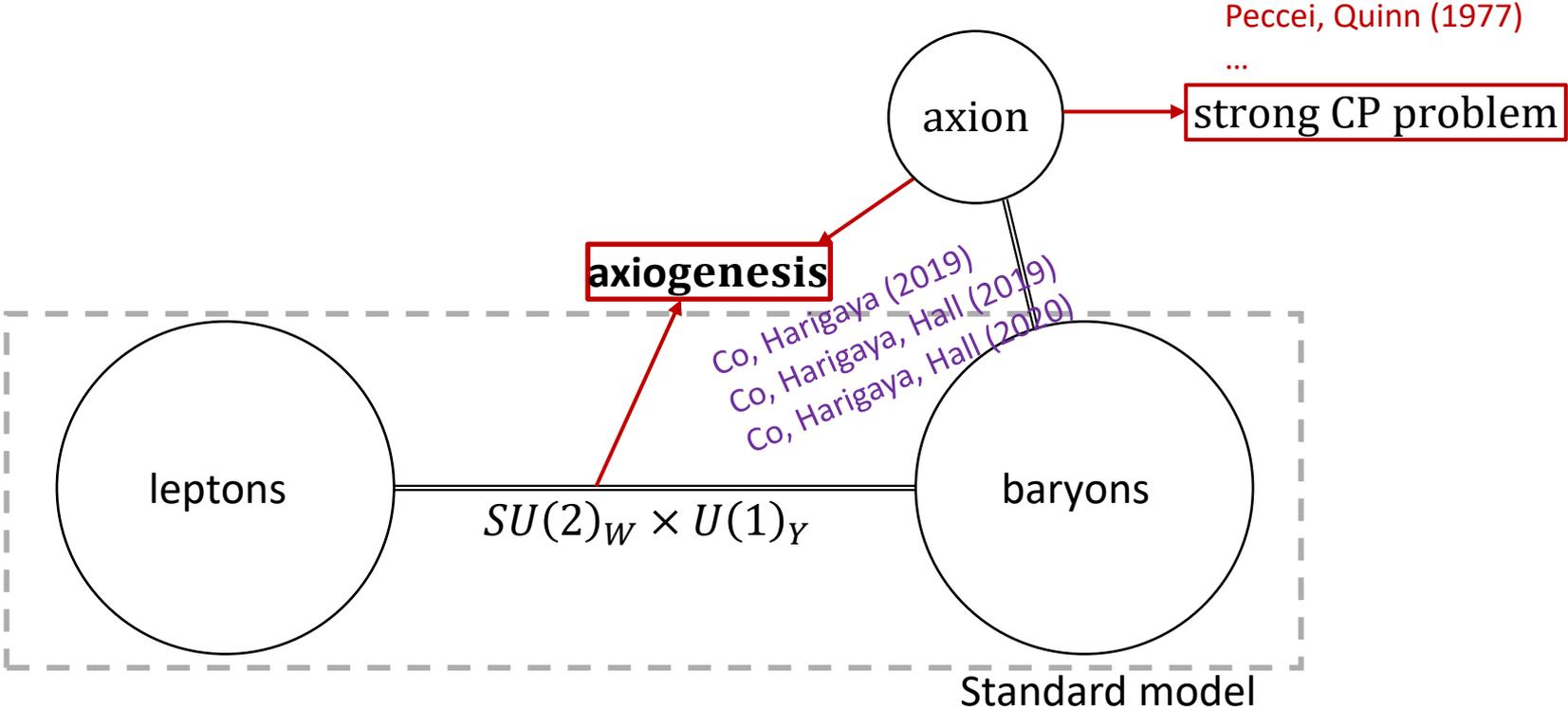$L_c, \; B - L_{SM}$: broken explicitly

$(B - L_{SM})$-genesis at $T \sim M$ scale?

possible by itself, but requires some tuning in UV

Grossman, Tsai (2008)

Kinetic misalignment
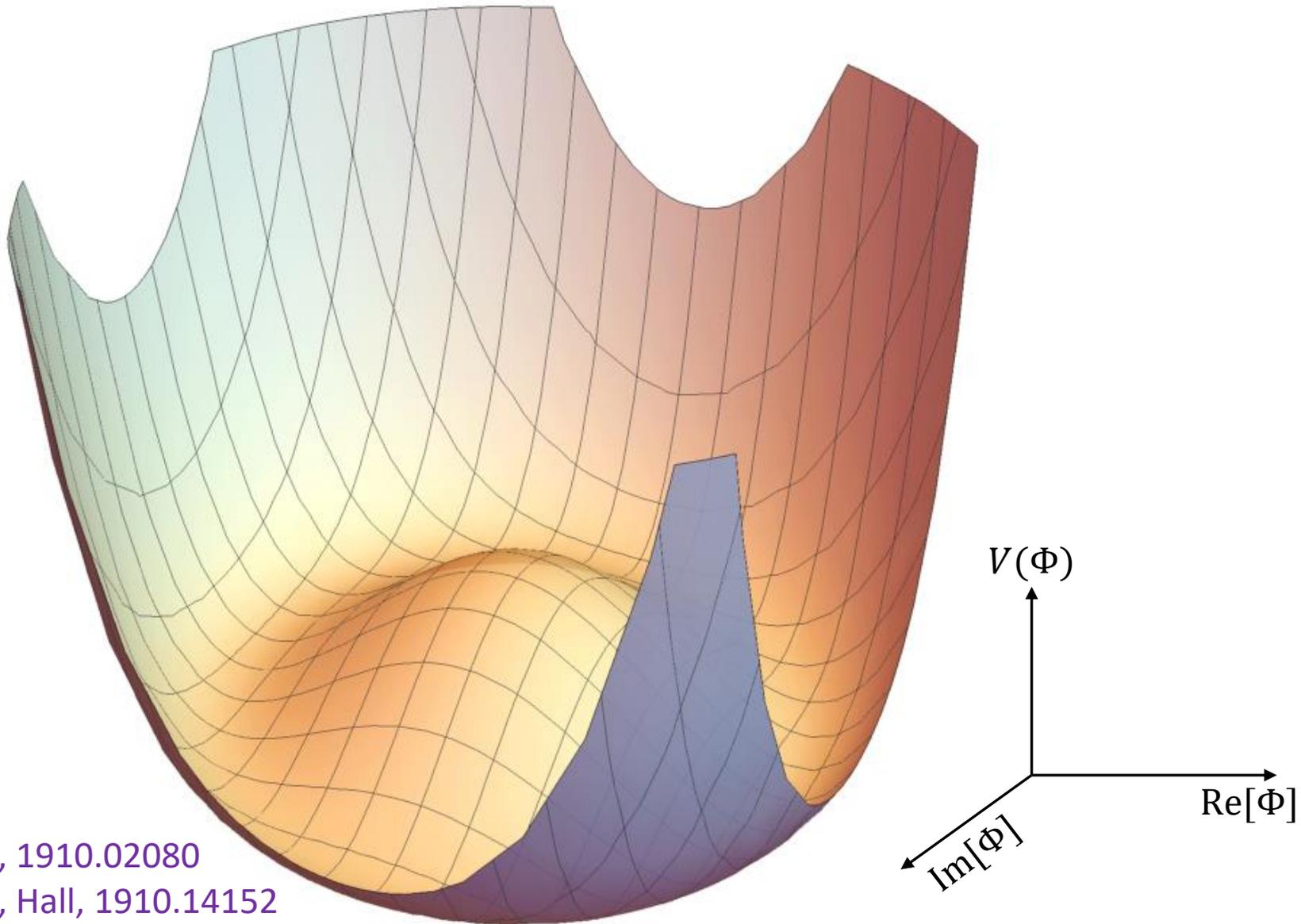
axion

strong CP problem

Peccei, Quinn (1977)
...

axiogenesis

Co, Harigaya (2019)
Co, Harigaya, Hall (2019)
Co, Harigaya, Hall (2020)

leptons

$SU(2)_W \times U(1)_Y$

baryons

Standard model

SA: Junichiro's talk

Kinetic misalignment

$V(\Phi)$

$Re[\Phi]$

$Im[\Phi]$

Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

Potential of PQ breaking field Φ

Kinetic misalignment

randomly picked up
by quantum fluctuation
during inflation

$V(\Phi)$

Re[Φ]

Im[Φ]

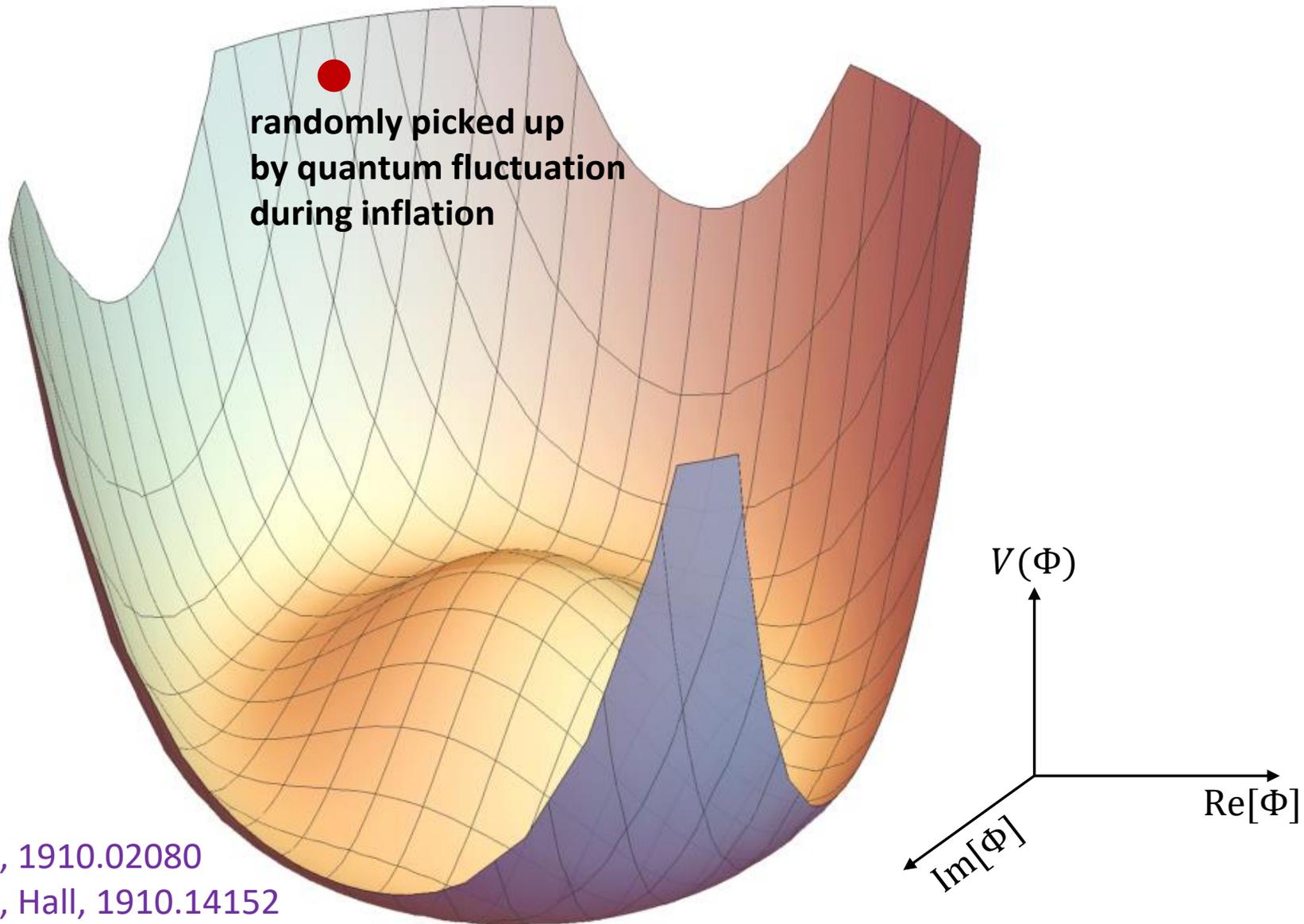Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

Potential of PQ breaking field Φ

Kinetic misalignment

Some explicit breaking
e.g. Φ^n/M_{Pl}^{n-4}

randomly picked up
by quantum fluctuation
during inflation

$V(\Phi)$

$\mathrm{Re}[\Phi]$

$\mathrm{Im}[\Phi]$

Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

Potential of PQ breaking field Φ

Kinetic misalignment

Some explicit breaking e.g. Φ^n/M_{Pl}^{n-4}

Axion

$V(\Phi)$

$\mathrm{Re}[\Phi]$

$\mathrm{Im}[\Phi]$
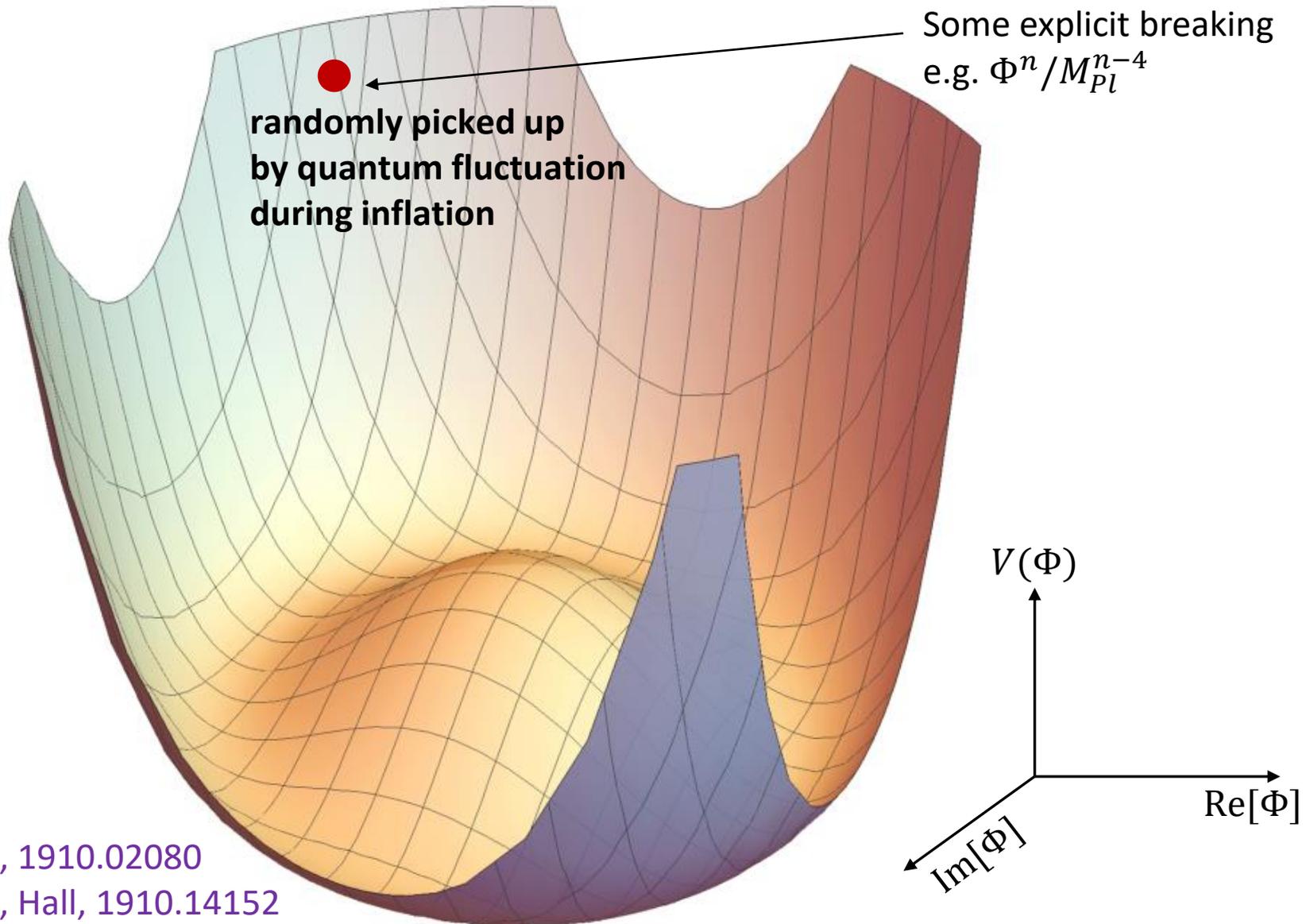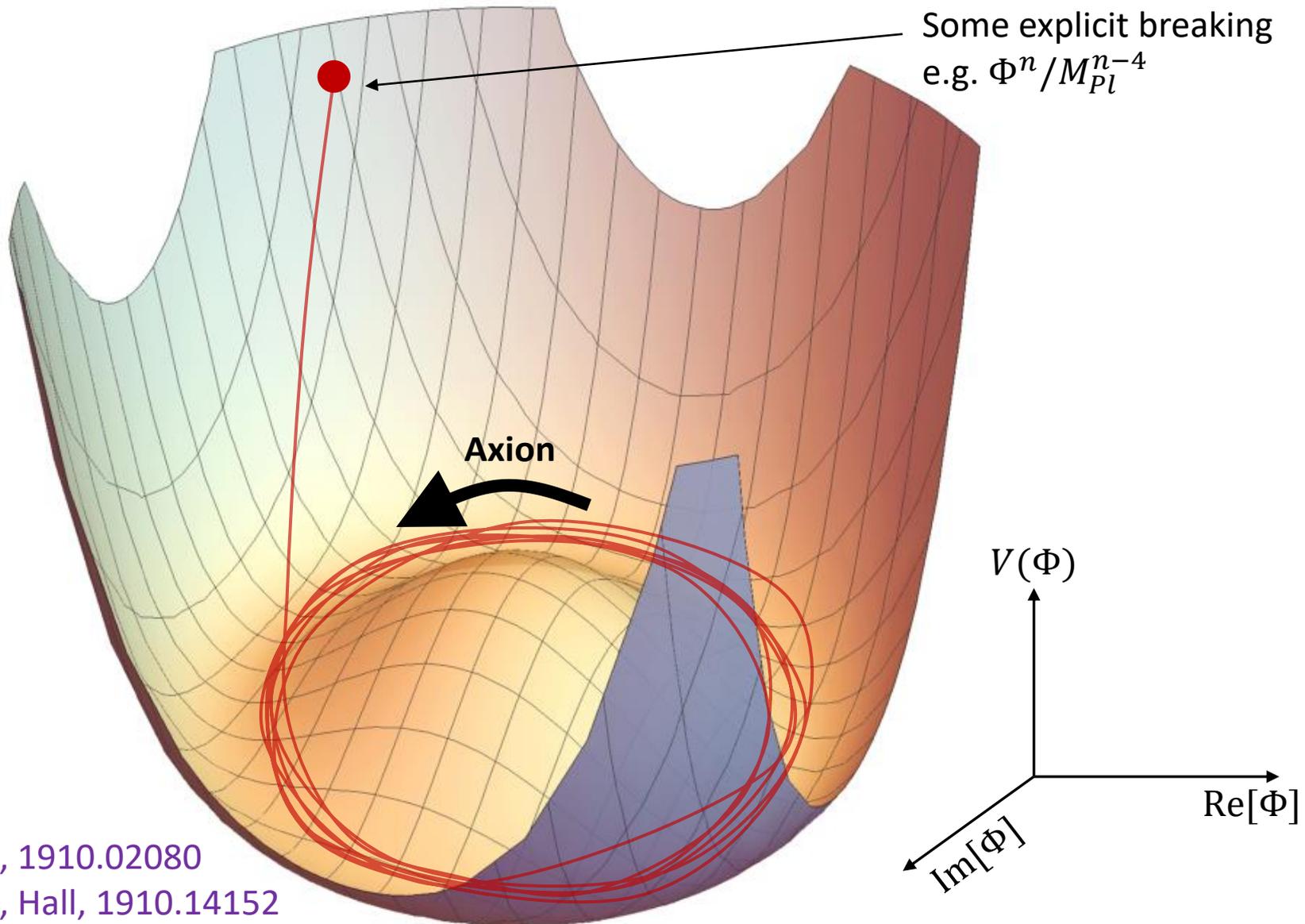
Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

Potential of PQ breaking field Φ

Evolution of the axion motion
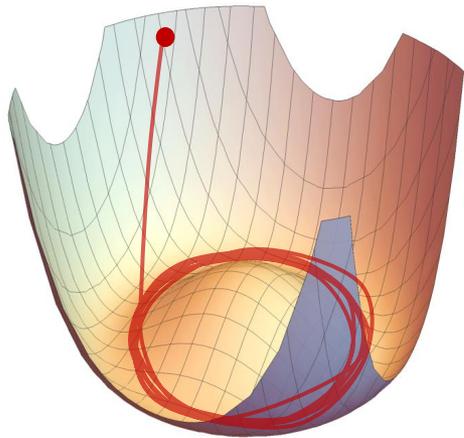
At $T_i \ll f_a$, $\quad \dot{a}(T_i) = \dot{a}_i \neq 0$

PQ charge from the axion motion is approximately conserved, so

$$\boldsymbol{Y_{PQ}} = \frac{n_{PQ}}{s} \simeq \frac{\dot{a}(T) f_a}{s} \simeq \text{const} \quad \Rightarrow \quad \dot{a}(T) \simeq \frac{Y_{PQ}}{f_a} s(T)$$

free parameter in this talk
(fixed by initial condition)

Maybe some modification
from QCD friction
(Alexandros' talk)

$m_\pi^2 f_\pi^2$

$a(t) \sim \dot{a} t$

slows down

as $\propto T^3$

a
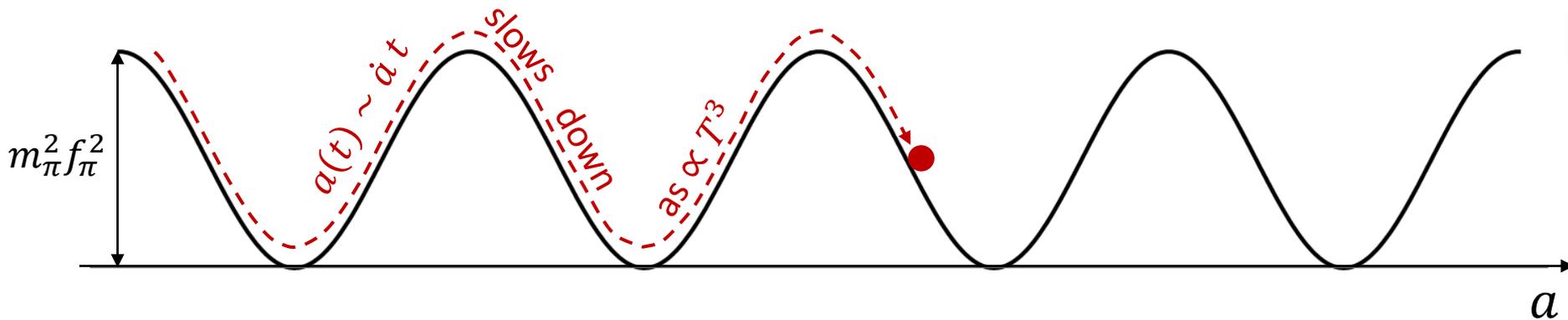
Axiogenesis

With $\dot{a} \neq 0$ background, Co, Harigaya (2019)

1. Chirality asymmetry is generated.

$$\frac{a}{f_a} G\tilde{G} \rightarrow \frac{a}{f_a} \partial_\mu J_A^\mu \rightarrow -\frac{\partial_\mu a}{f_a} J_A^\mu \rightarrow -\frac{\dot{a}}{f_a}(n_L - n_R)$$

2. Weak sphaleron converts only left-handed quarks into right-handed anti-leptons.

$$B = 0, L = 0$$
$$B - L = 0$$

$$B = -1, L = -1$$
$$B - L = 0$$

- ● quarks
- ● anti-quarks
- ● anti-leptons
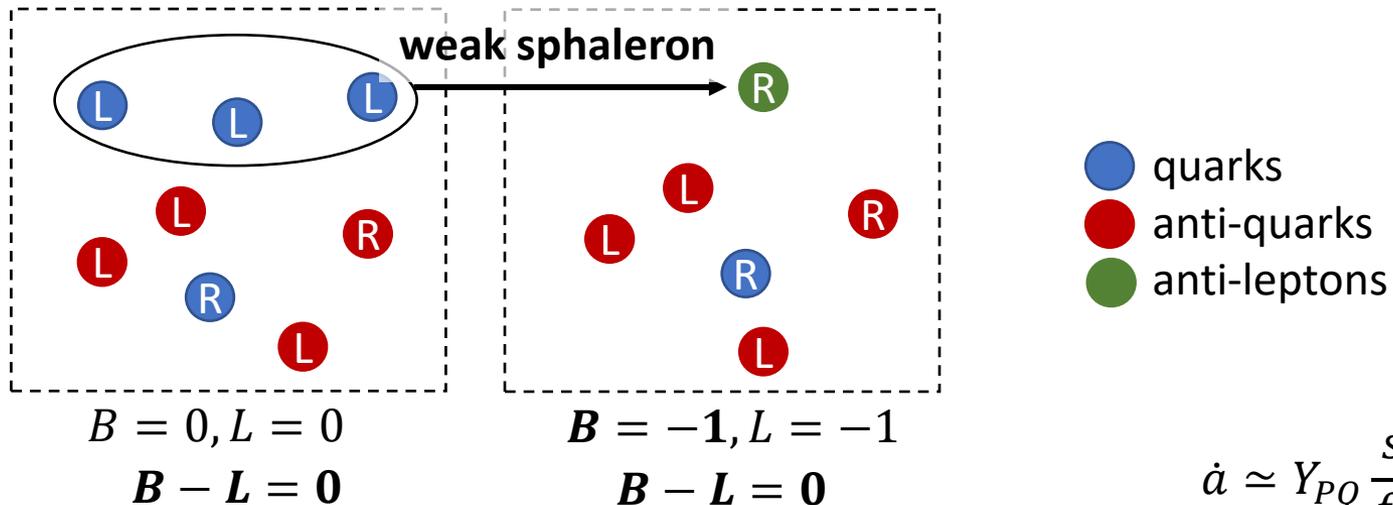
$$\dot{a} \simeq Y_{PQ} \frac{s}{f_a}$$

3. $(B + L)$-genesis

$$n_B \sim \mu_{B+L} T^2 \sim \frac{\dot{a}}{f_a} T^2 \sim Y_{PQ} \left(\frac{T}{f_a}\right)^2 s$$

Axion dark matter

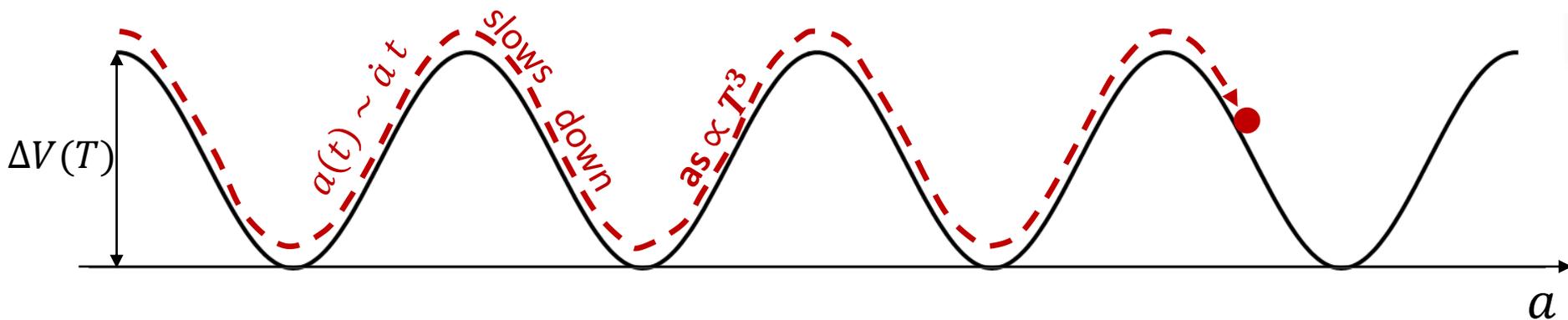QCD axion: $m_a \sim \dfrac{m_\pi f_\pi}{f_a}$

$\Delta V(T)$

$a(t) \sim \dot{a}\, t$ slows down as $\propto T^3$

a

$\cdots$

$$\eta_B = \frac{n_B}{s} \sim Y_{PQ} \left(\frac{T}{f_a}\right)^2$$

Axion dark matter

QCD axion: $m_a \sim \dfrac{m_\pi f_\pi}{f_a}$

$\Delta V(T)$

$a(t) \sim \dot{a} \, t$ slows down

as $\propto T^3$

a

$\hookrightarrow \Gamma_{ws} \propto \exp(-v_h/T) < H$

$\cdots$

$$\eta_B = \frac{n_B}{s} \sim Y_{PQ}\left(\frac{T}{f_a}\right)^2$$

$$Y_{PQ}\left(\frac{T_{EW}}{f_a}\right)^2$$

$\sim 10^{-10}$

EWPT

$T \simeq T_{EW}$

Axion dark matter

QCD axion: $m_a \sim \dfrac{m_\pi f_\pi}{f_a}$

$\dot{a}(T_{trap})^2 \sim \Delta V(T_{trap})$

$a(t) \sim \dot{a} t$

slows down

as $\propto T3$

$\Delta V(T)$

$\rightarrow \Gamma_{ws} \propto \exp(-v_h/T) < H$

$\cdots$

$\eta_B = \dfrac{n_B}{s} \sim Y_{PQ}\left(\dfrac{T}{f_a}\right)^2$

$Y_{PQ}\left(\dfrac{T_{EW}}{f_a}\right)^2$

$\sim 10^{-10}$

EWPT

$T \simeq T_{EW}$

$a(t) \propto \cos(m_a t)$

Dark matter

$\dfrac{\rho_{DM}}{s} \sim m_a Y_{PQ}$
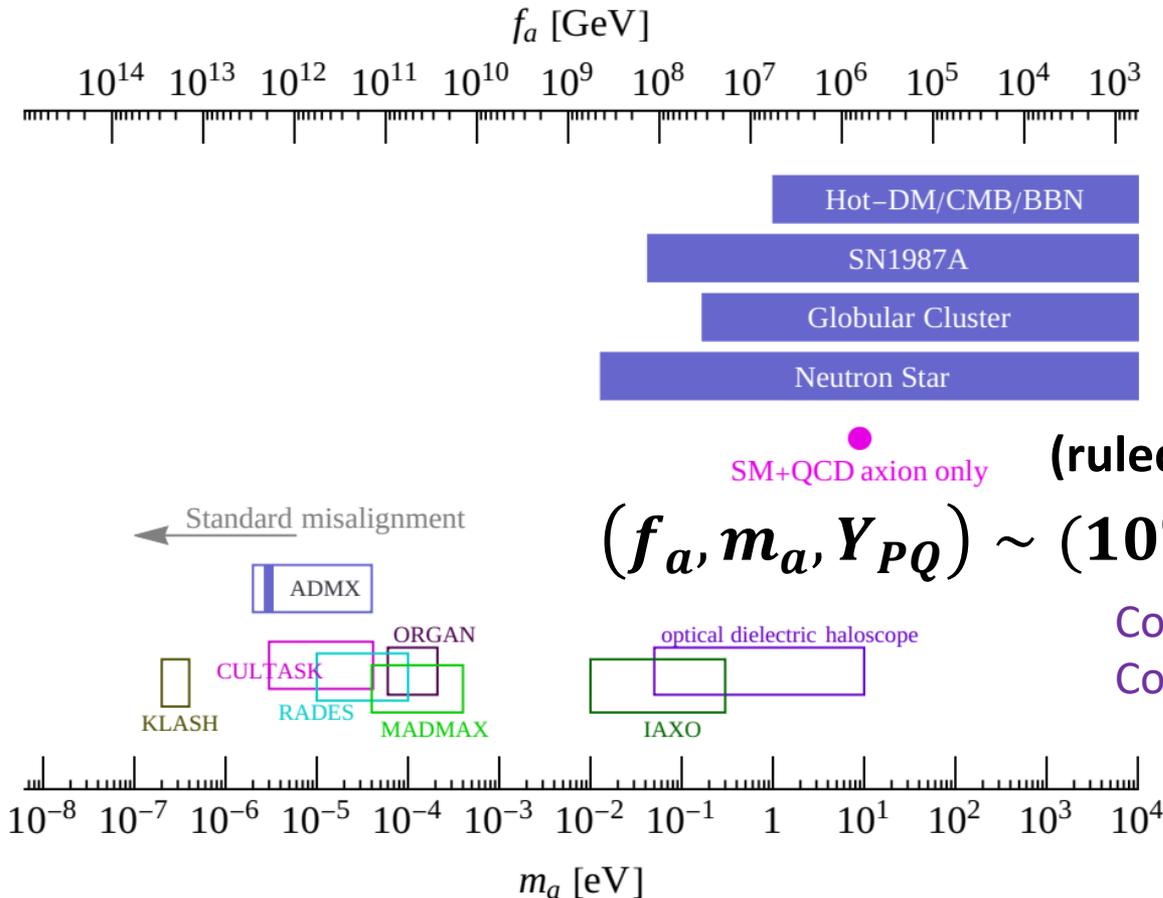
$\sim 10^{-10}\text{GeV}$
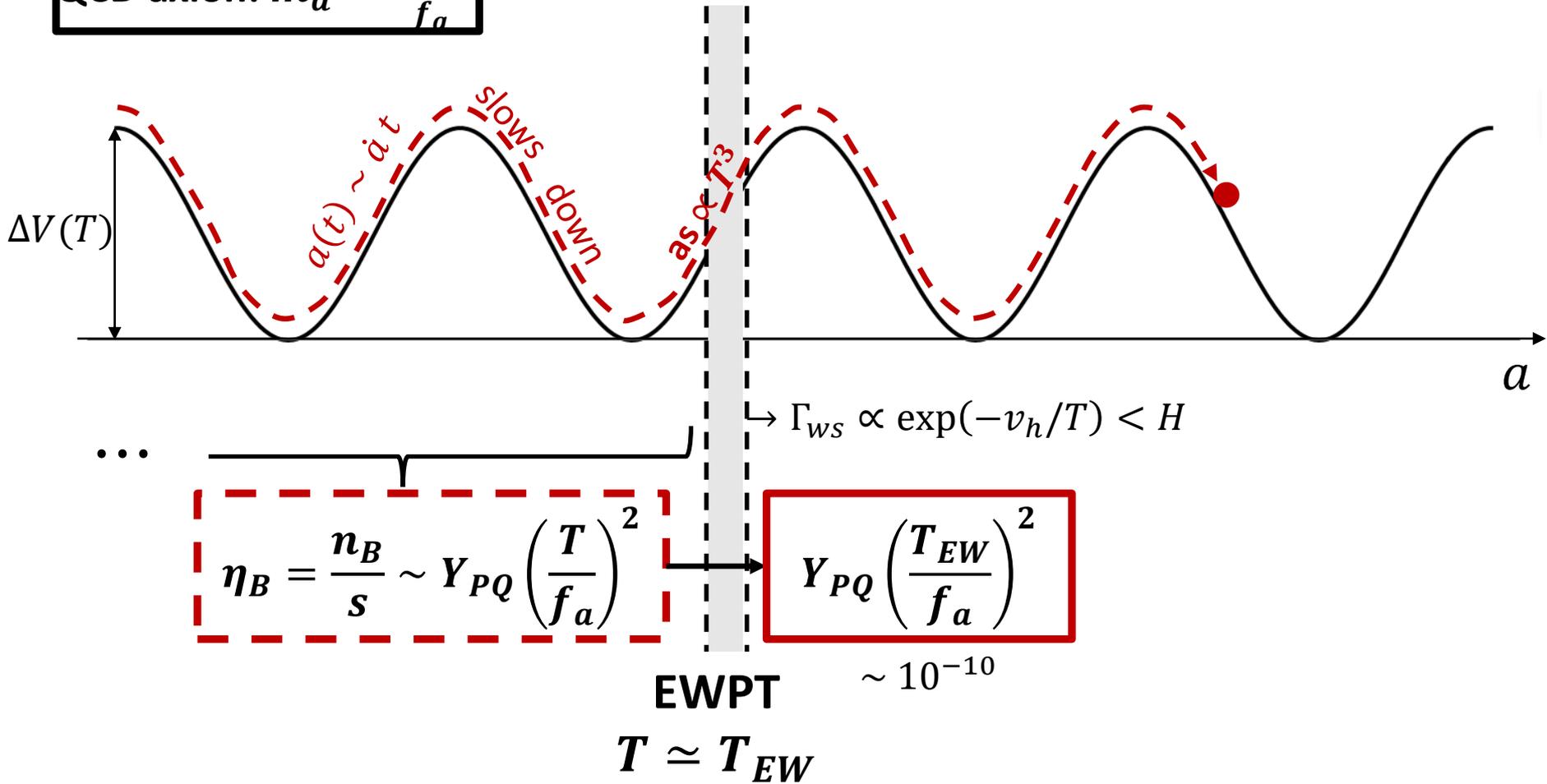
a
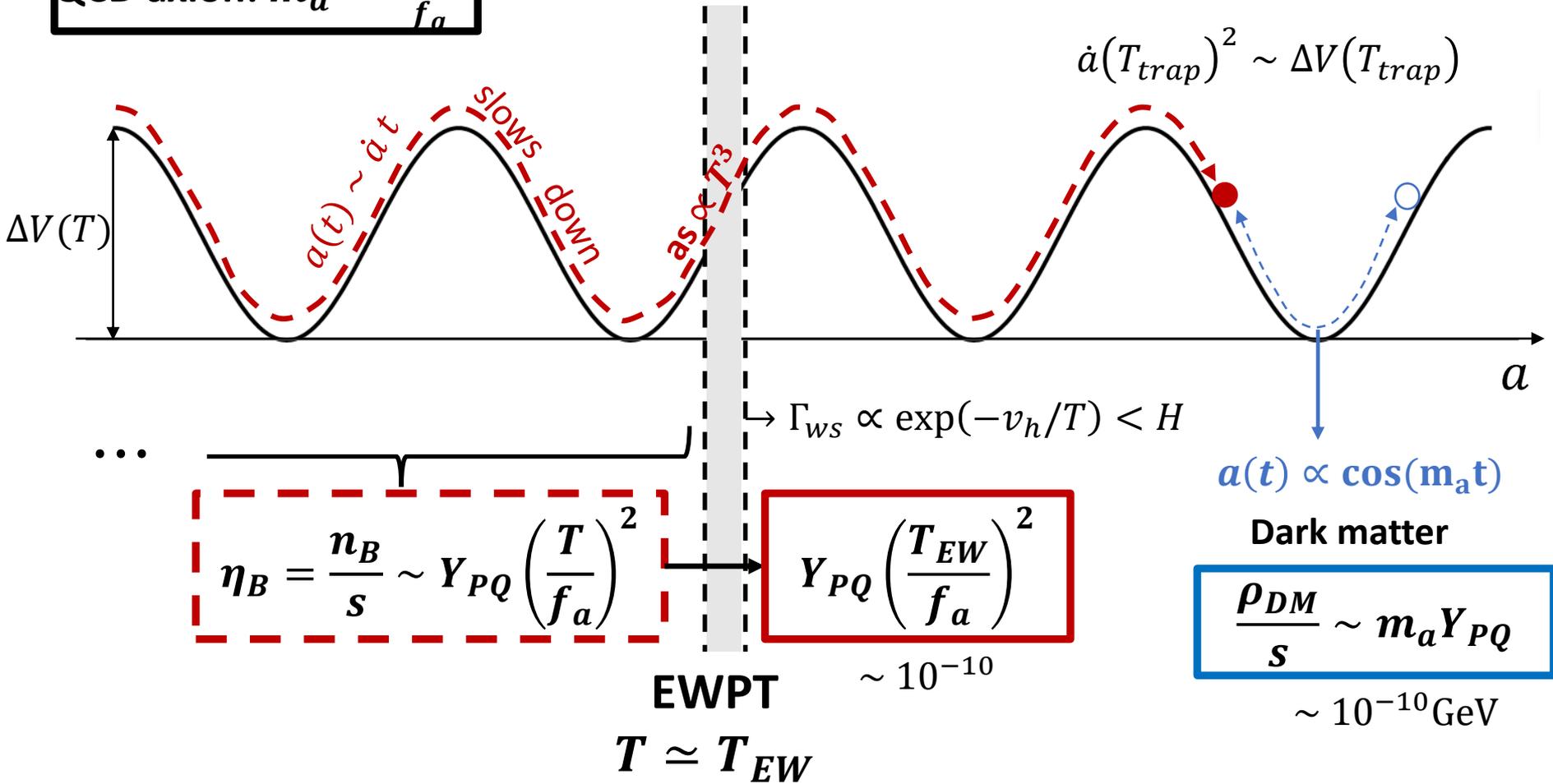
Strong CP problem, baryon asymmetry, dark matter

$$\boxed{m_a f_a \sim m_\pi f_\pi}$$

$$\boxed{Y_{PQ}\left(\frac{T_{EW}}{f_a}\right)^2 \sim 10^{-10}}$$

$$\boxed{m_a Y_{PQ} \sim 0.1\ \text{eV}}$$

f_a [GeV]

10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3}

Hot−DM/CMB/BBN

SN1987A

Globular Cluster

Neutron Star

SM+QCD axion only

(ruled out)

Standard misalignment

ADMX

ORGAN

CULTASK

RADES

MADMAX

KLASH

optical dielectric haloscope

IAXO

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4}

m_a [eV]

$$\left(f_a, m_a, Y_{PQ}\right) \sim \left(10^6\,\text{GeV}, 10\ \text{eV}, 10^{-2}\right)$$

Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

composite
sector

axion

strong CP problem

small Dirac m$_\nu$

Cogenesis

leptons

$SU(2)_W \times U(1)_Y$

baryons

Standard model
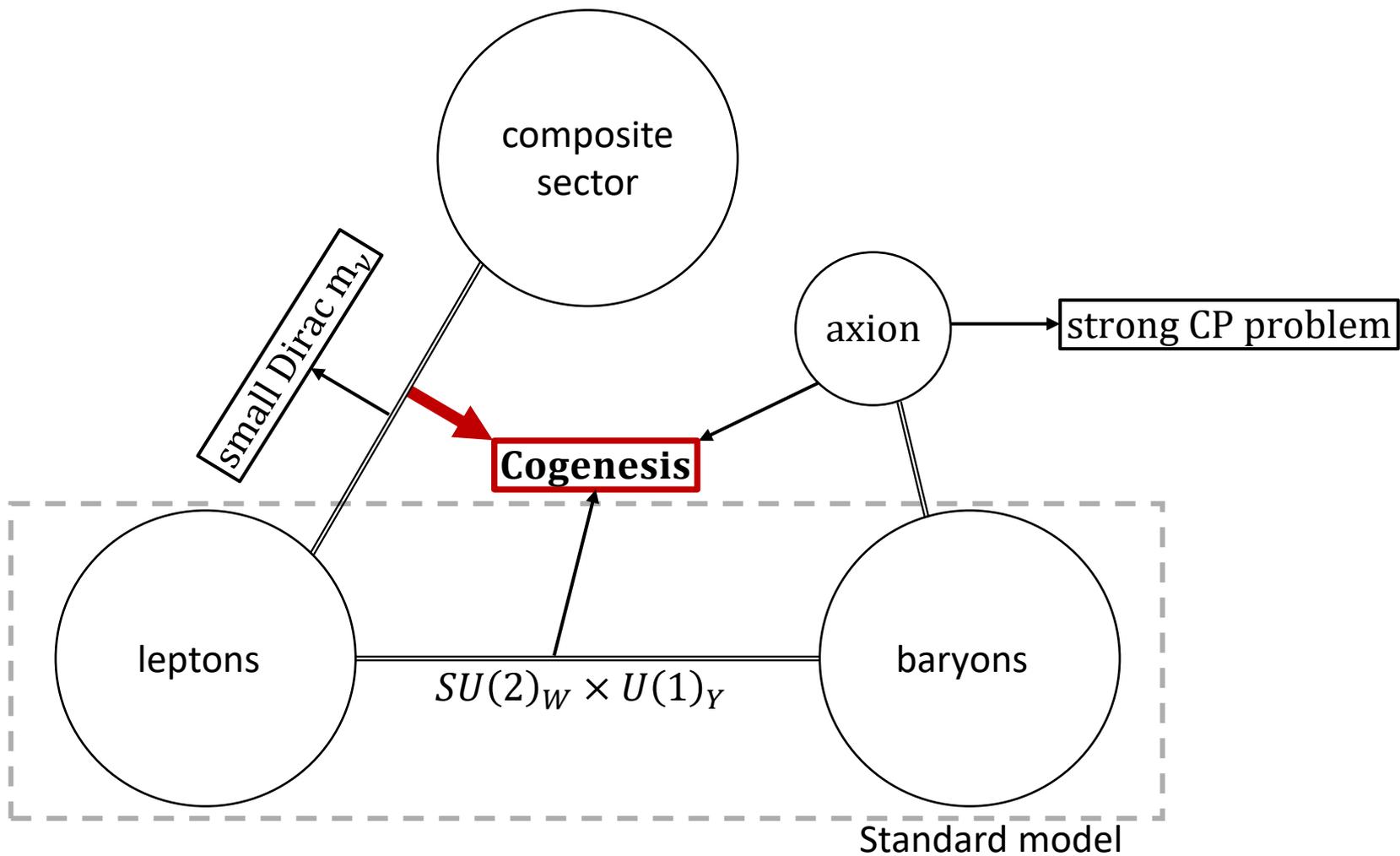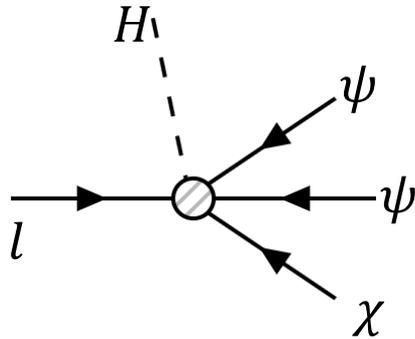
$$L = L_{SM} + L_c$$

$$\frac{1}{M^3} Hl\,(\psi\psi\chi)$$

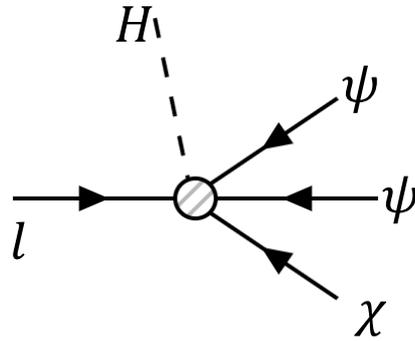$$L_{SM} \leftrightarrow L_c$$

Active at high $T > T_{LD} \sim 0.1M$

LD: (composite) Lepton Decoupling (chemically)

with composite Dirac ν
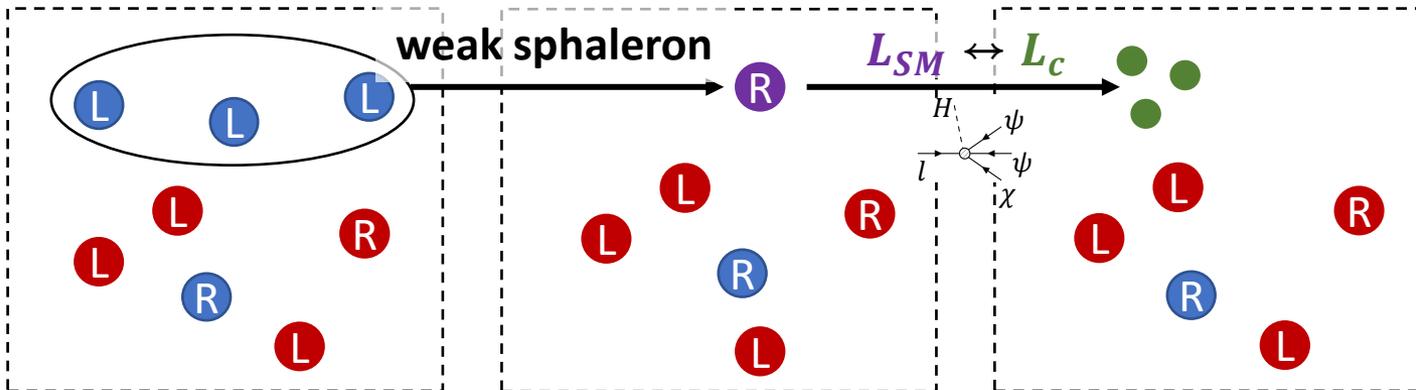
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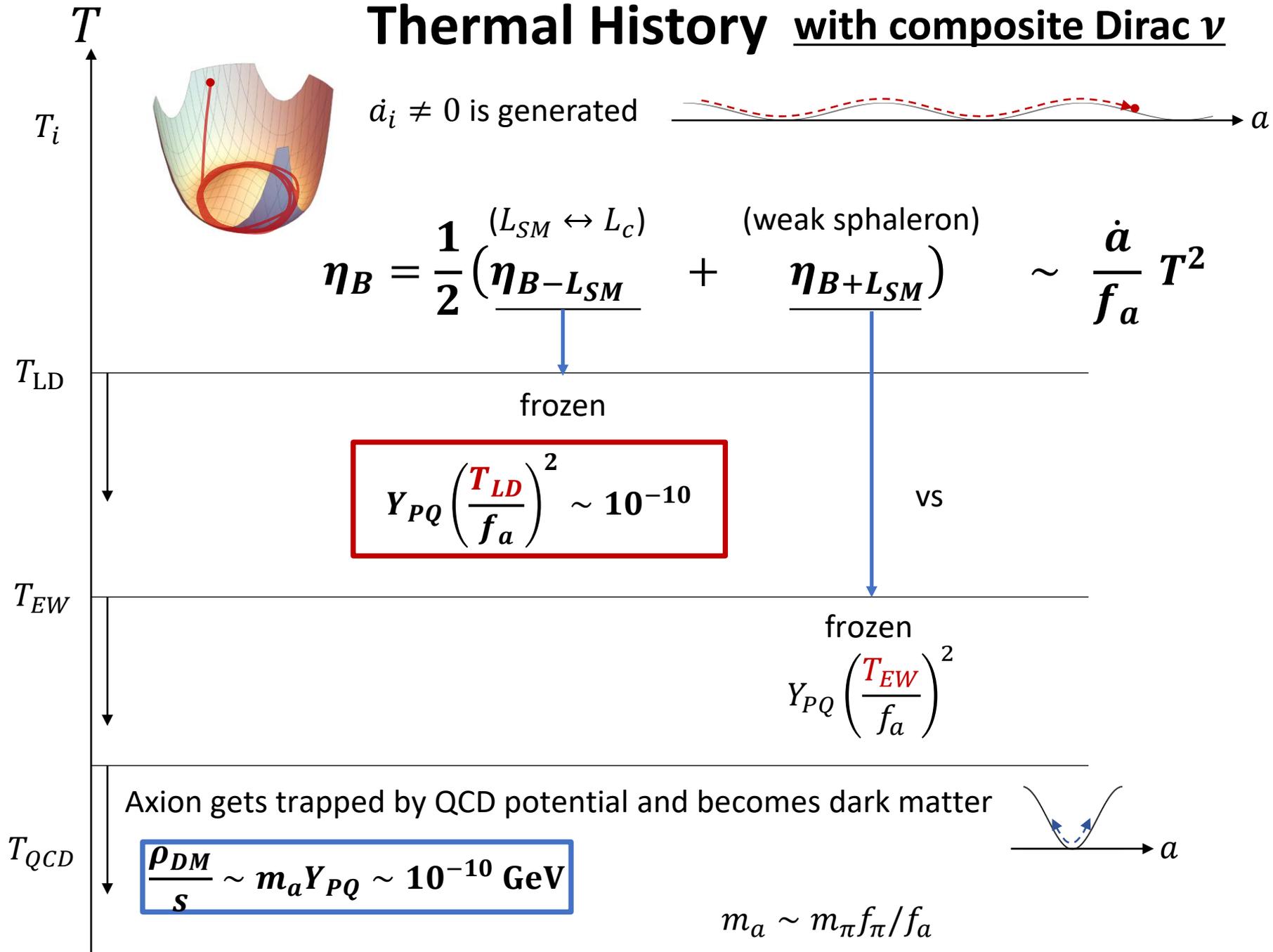
$$\frac{1}{M^3} H l \, (\psi\psi\chi)$$

weak sphaleron

$L_{SM} \leftrightarrow L_c$

- quarks
- anti-quarks
- anti-leptons
- composite sector

$B = 0, L = 0$
$L_{SM} = 0, L_c = 0$
$\boldsymbol{B + L_{SM} = 0}$
$\boldsymbol{B - L_{SM} = 0}$

$\boldsymbol{B = -1}, L = -1$
$L_{SM} = 1, L_c = 0$
$\boldsymbol{B + L_{SM} = -2}$
$\boldsymbol{B - L_{SM} = 0}$

$\boldsymbol{B = -1}, L = -1$
$L_{SM} = 0, L_c = 1$
$\boldsymbol{B + L_{SM} = -1}$
$\boldsymbol{B - L_{SM} = -1}$

Thermal History with composite Dirac ν

T

T_i

$\dot{a}_i \neq 0$ is generated

$$\eta_B = \frac{1}{2}(\underbrace{\eta_{B-L_{SM}}}_{(L_{SM} \leftrightarrow L_c)} + \underbrace{\eta_{B+L_{SM}}}_{\text{(weak sphaleron)}}) \sim \frac{\dot{a}}{f_a}T^2$$

T_{LD}

frozen

$$Y_{PQ}\left(\frac{T_{LD}}{f_a}\right)^2 \sim 10^{-10}$$

vs

T_{EW}

frozen

$$Y_{PQ}\left(\frac{T_{EW}}{f_a}\right)^2$$

Axion gets trapped by QCD potential and becomes dark matter

T_{QCD}

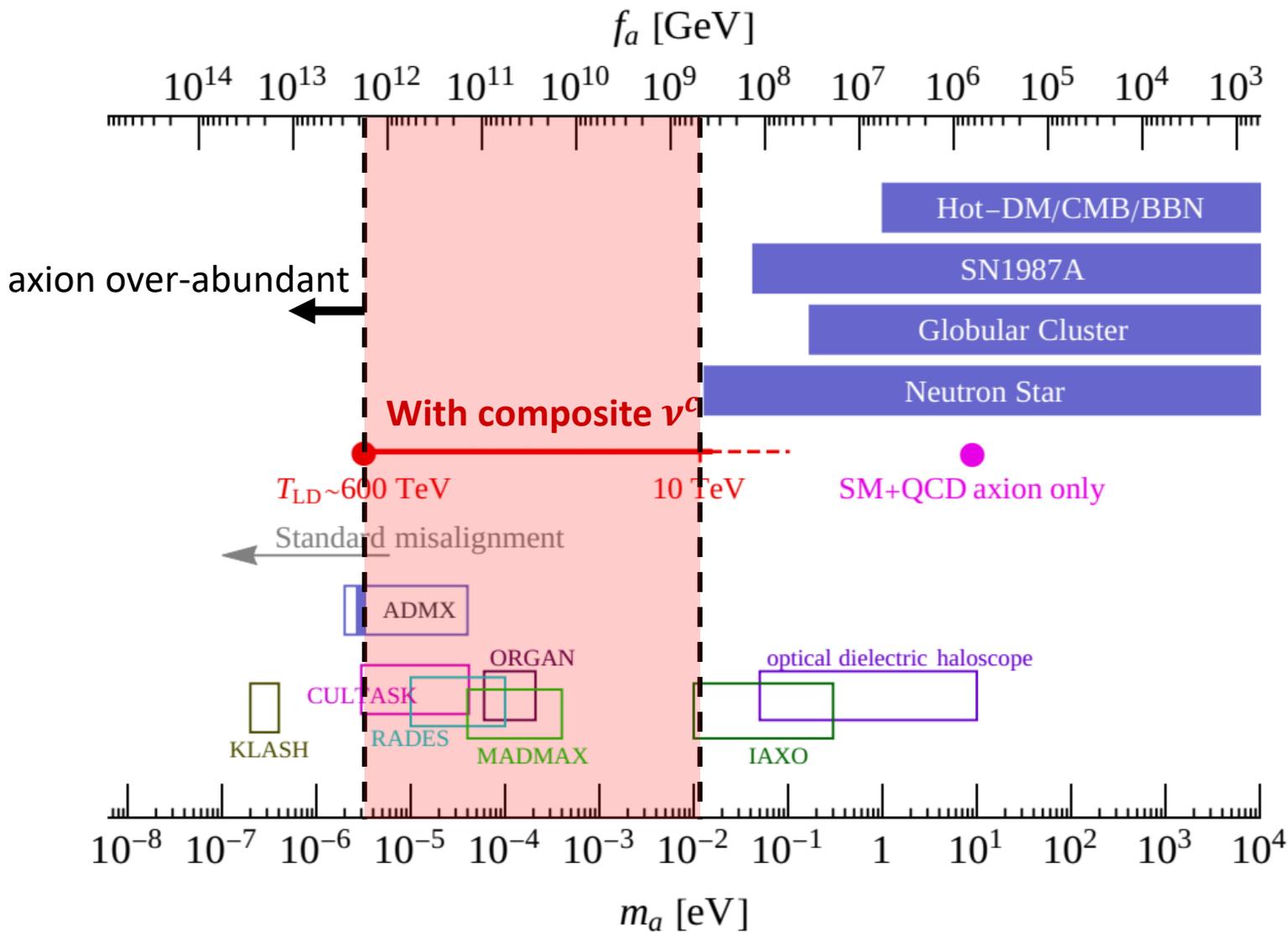$$\frac{\rho_{DM}}{s} \sim m_a Y_{PQ} \sim 10^{-10} \text{ GeV}$$

$$m_a \sim m_\pi f_\pi / f_a$$

Baryogenesis with composite Dirac ν
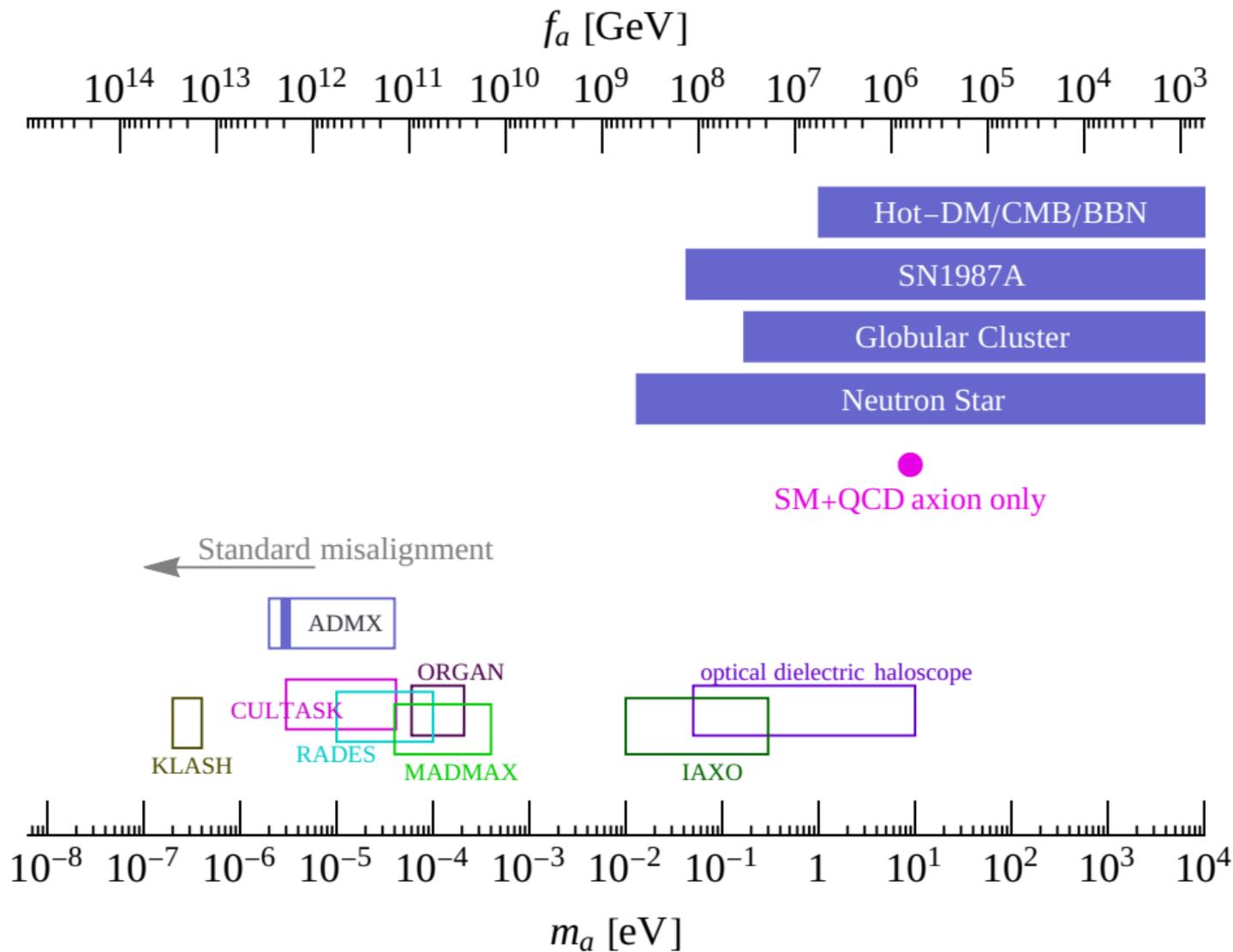
Baryogenesis with composite Dirac ν
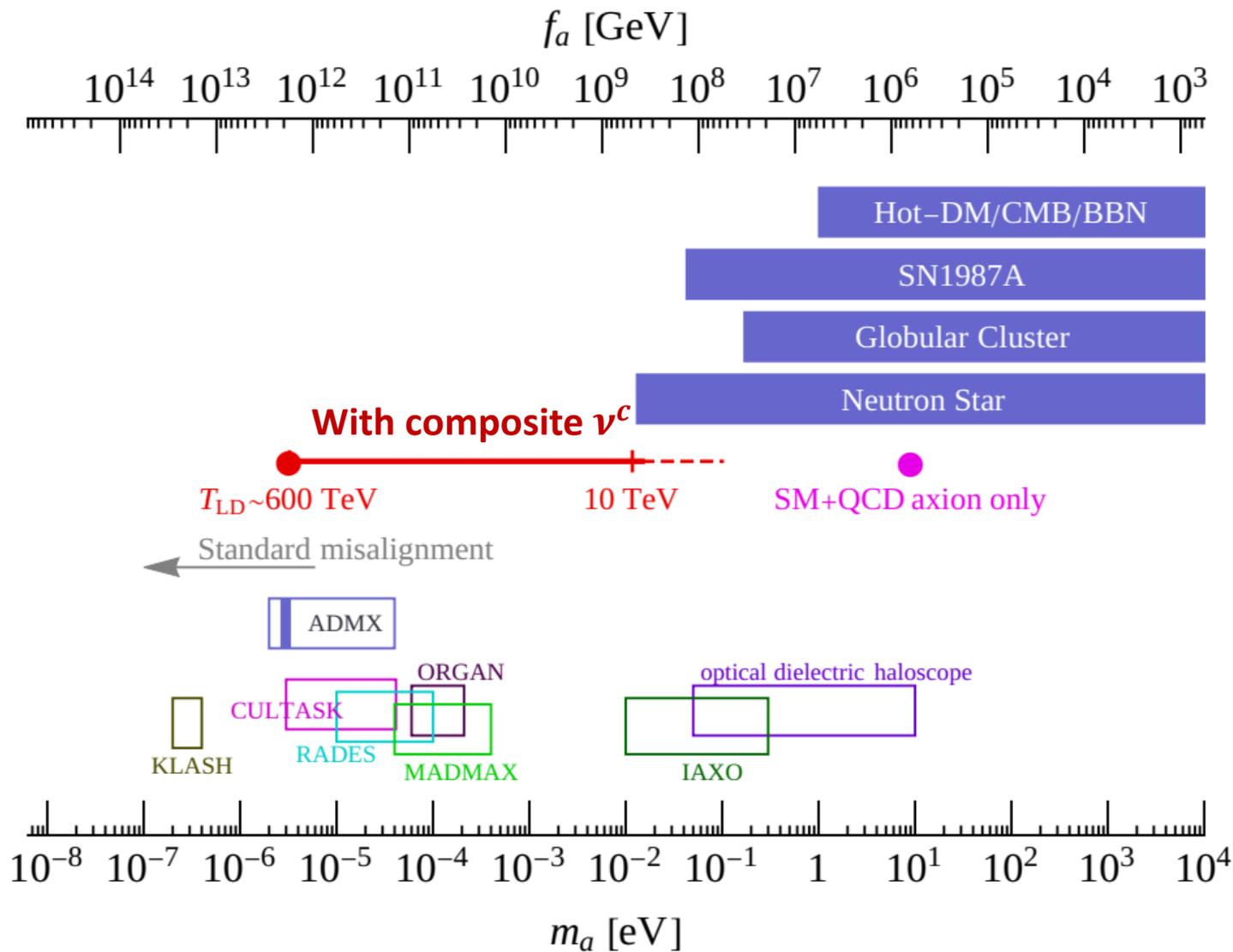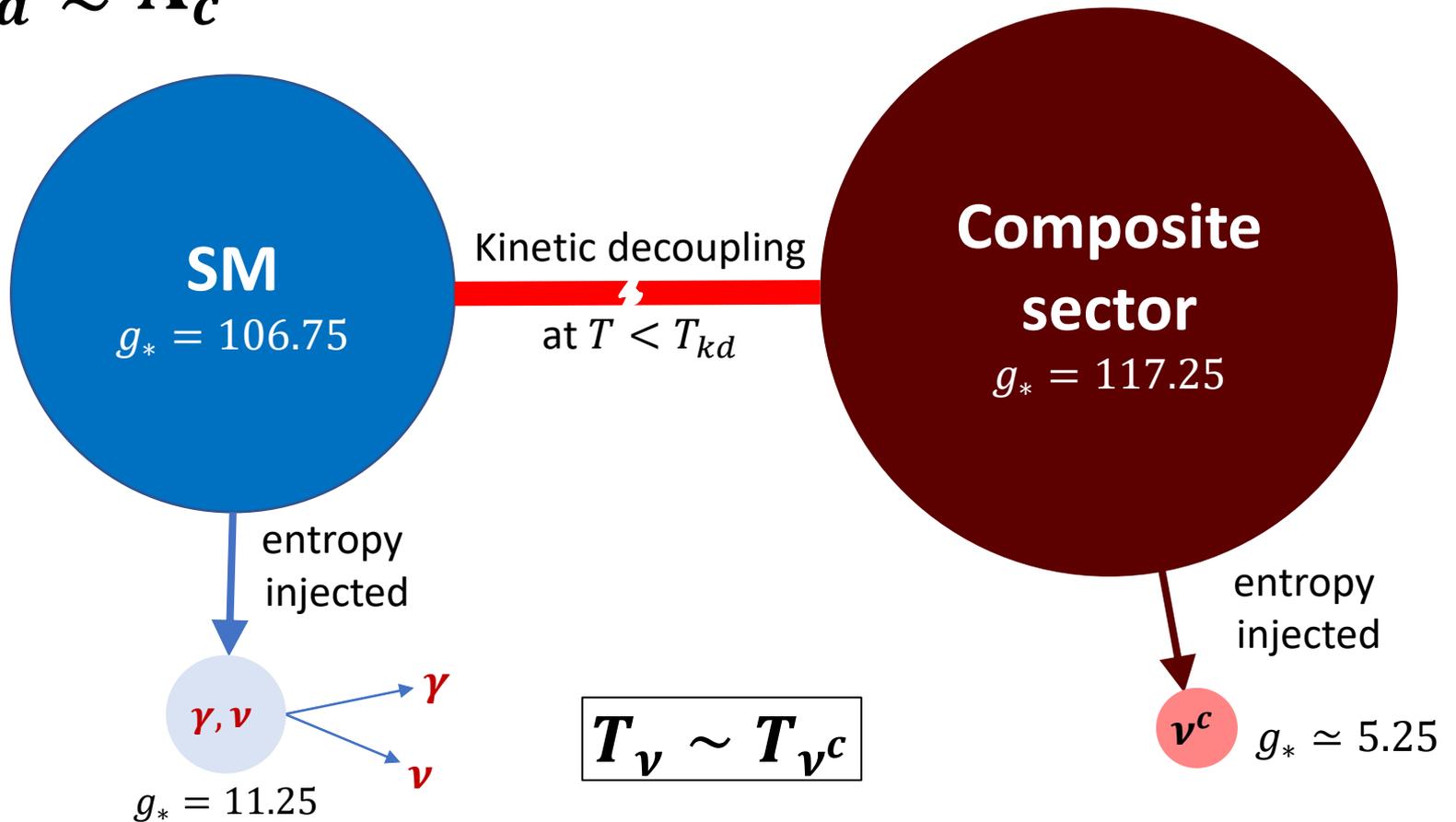
Baryogenesis with composite Dirac ν

$$\Delta N_{eff} \text{ from } \nu^c \text{ ?}$$

Thermal production required for baryogenesis

ΔN_{eff}

If $T_{kd} \gtrsim \Lambda_c$

SM
$g_* = 106.75$

Kinetic decoupling
at $T < T_{kd}$

Composite sector
$g_* = 117.25$

entropy injected

γ, ν
$g_* = 11.25$

γ

ν

$T_\nu \sim T_{\nu^c}$

entropy injected

ν^c $g_* \simeq 5.25$

$$\Delta N_{eff} \simeq 8.8$$

ruled out!

ΔN_{eff}

If $T_{kd} \ll \Lambda_c$

SM
$g_* = 106.75$

Kinetic decoupling
at $T < T_{kd}$

Composite sector

ν^c

$g_* \simeq 5.25$

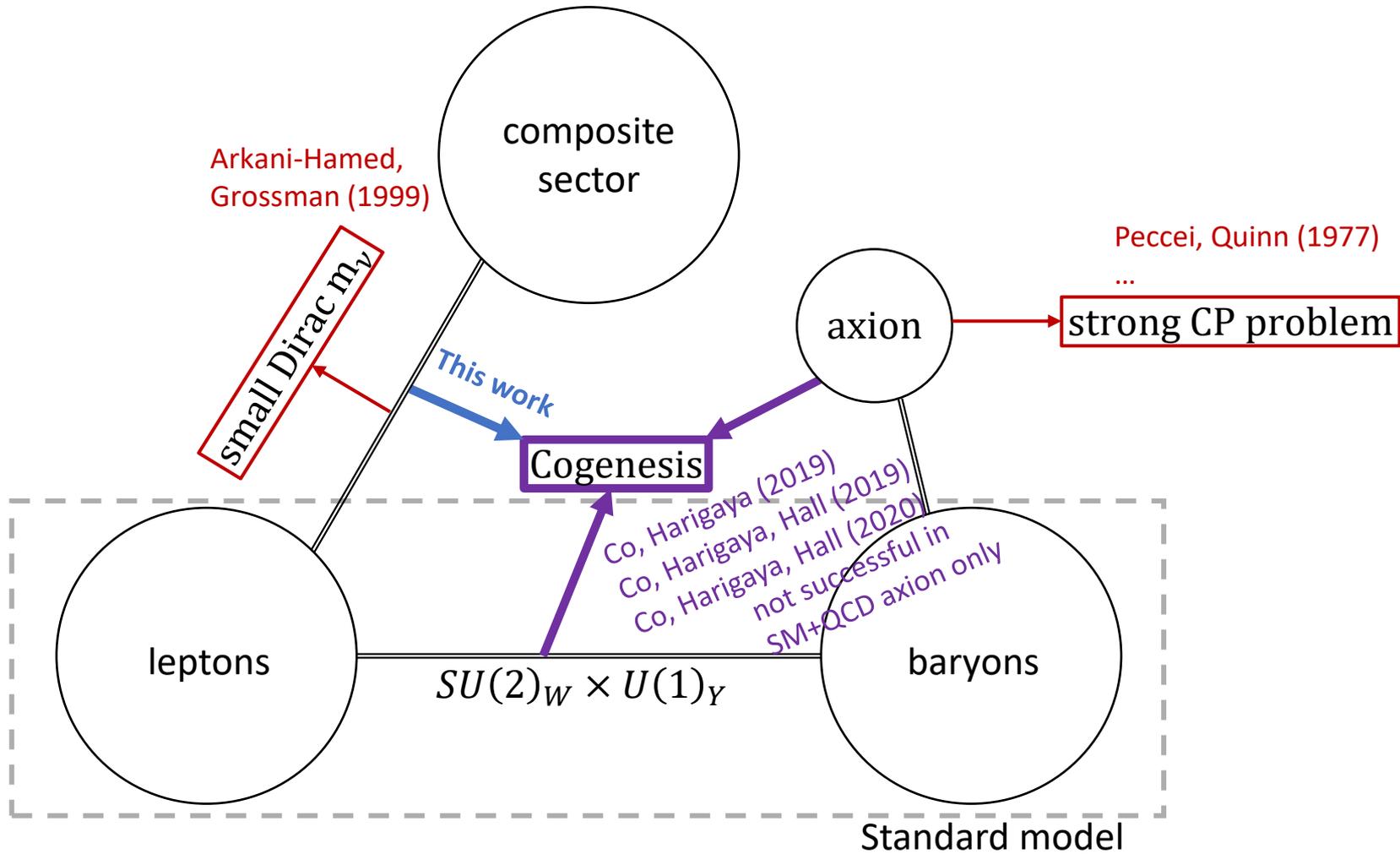entropy injected

γ, ν

γ

ν

$g_* = 11.25$

$$T_\nu \gg T_{\nu^c}$$
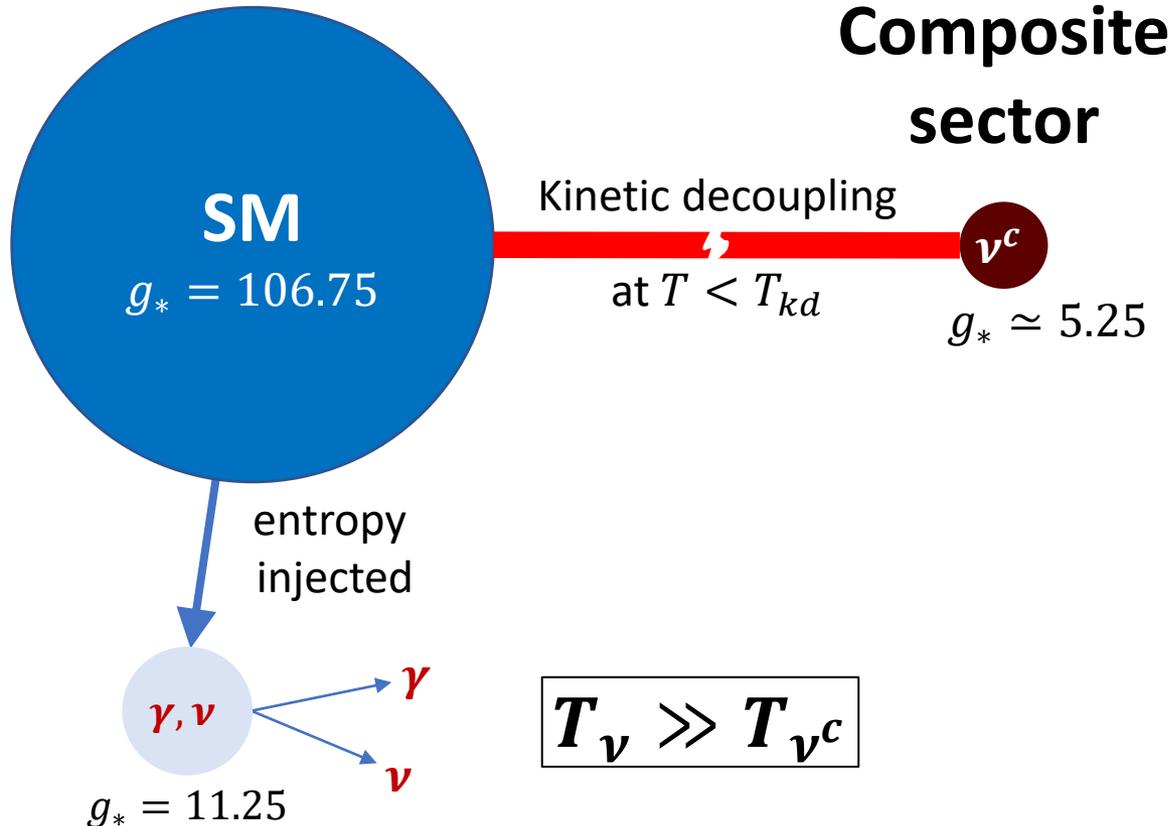
$$\Delta N_{\text{eff}} \gtrsim 0.14$$

Not ruled out, and testable in future

CMB stage IV: $\Delta N_{\text{eff}} < 0.03$

Summary

Summary

& $\boxed{\Delta N_{\text{eff}} \gtrsim 0.14}$

& No $0\nu\beta\beta$
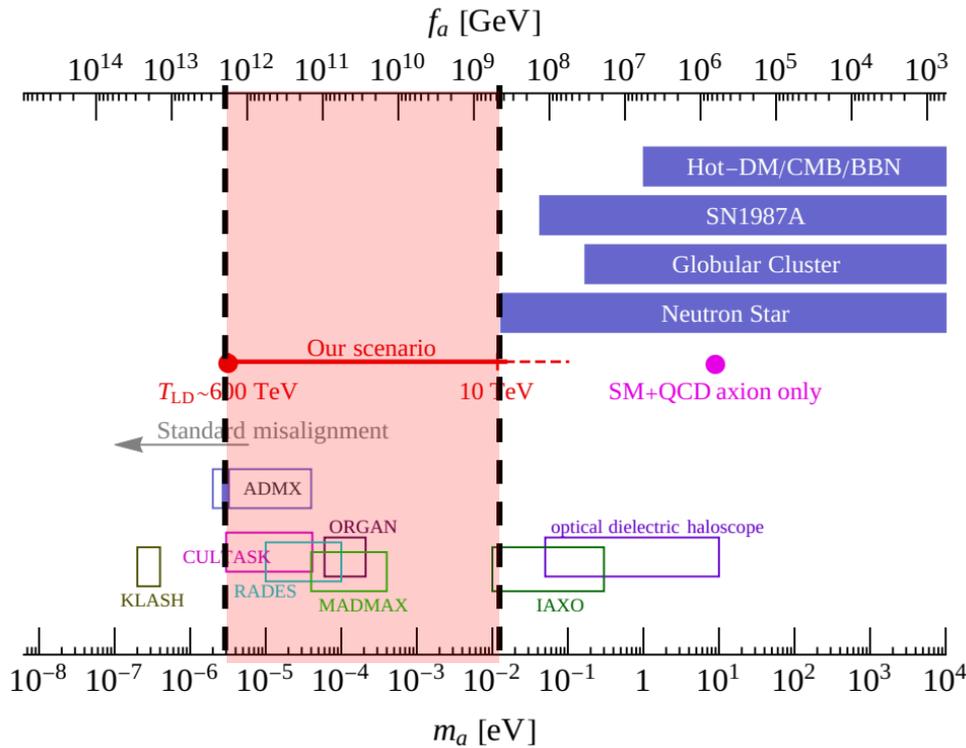
$m_a > \mu\text{eV}$
$f_a < 10^{12}\text{GeV}$

axiogenesis   **composite ν^c**